EECS 245   ELECTRONICS

Textbook   Electronics, 2/e
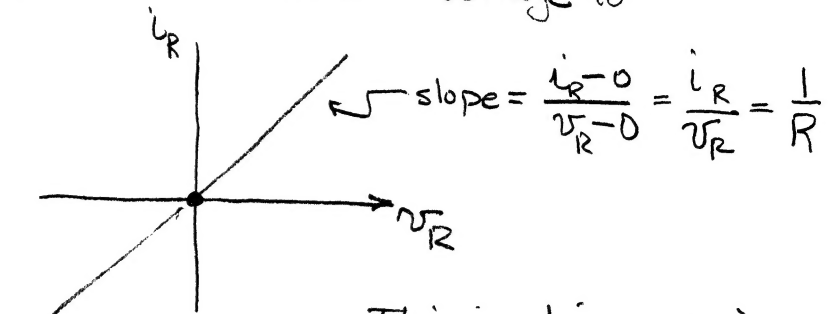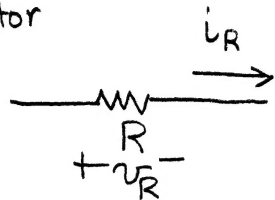   Prentice-Hall

diode two terminal device

i-v characteristic curve

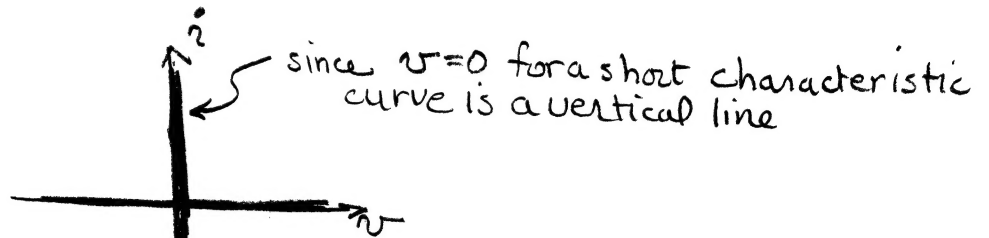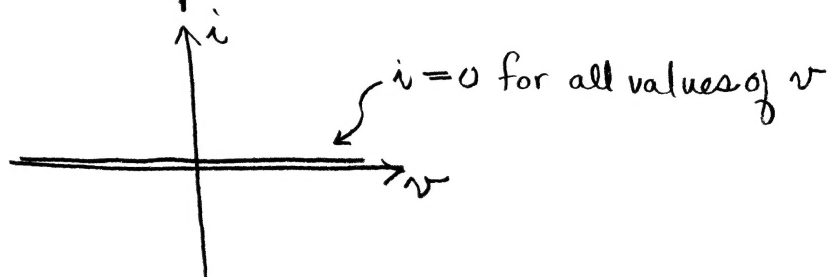for electronic devices we can plot current versus voltage to characterize the device:

Resistor

i_R

$\xrightarrow{\hspace{1cm}}$

—\/\/\/—

R

$+v_R-$

slope $= \dfrac{i_R - 0}{v_R - 0} = \dfrac{i_R}{v_R} = \dfrac{1}{R}$

i_R (vertical axis)

v_R (horizontal axis)

This is a linear device.

what does a wire look like?

a short

since $v = 0$ for a short characteristic curve is a vertical line

i (vertical axis)

v (horizontal axis)

an open

$i = 0$ for all values of v

i (vertical axis)

v (horizontal axis)

basic diode characteristics

anode —————$\triangleright|$————— cathode

i_D (above)

$+ \; v_D \; -$
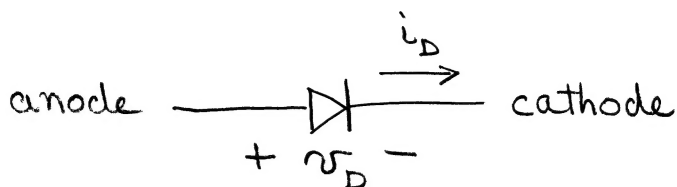
If we hook up a variable power supply we can measure
the i-v characteristics of this device

forward bias
$v_D > 0$
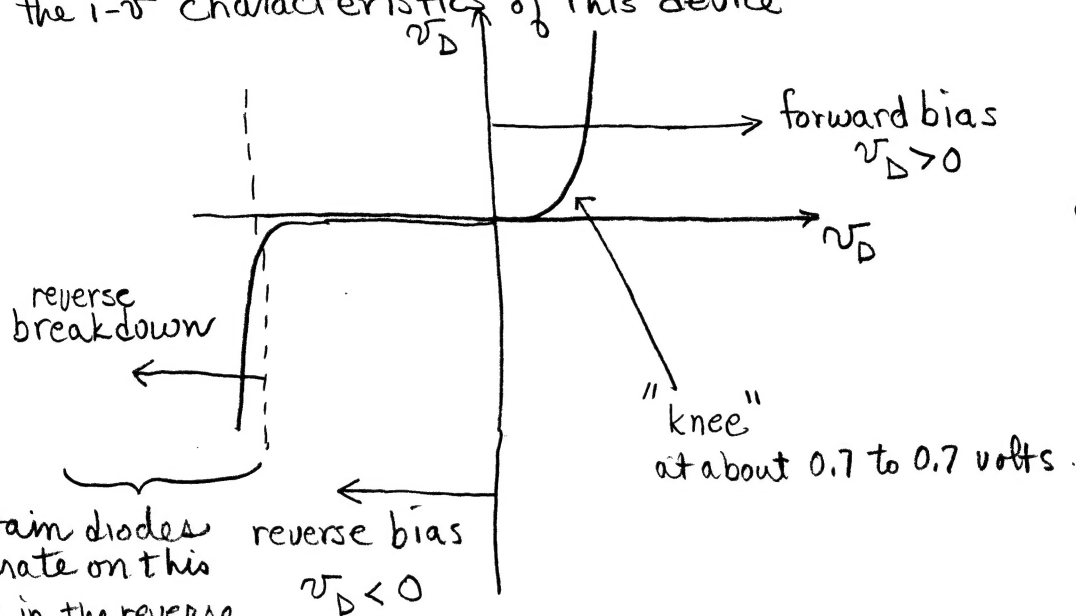
A diode is
a non-linear
device.

v_D (axis)

reverse
breakdown

"knee"
at about 0.7 to 0.7 volts.

reverse bias
$v_D < 0$

Certain diodes
operate on this
line in the reverse
breakdown
region. They
are called "zener"
diodes.

.available as diodes
with specified breakdown
voltages.
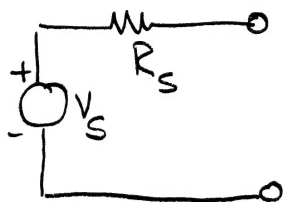
Examples of diodes we will use
in lab:

1N914 } low power switching
1N4148

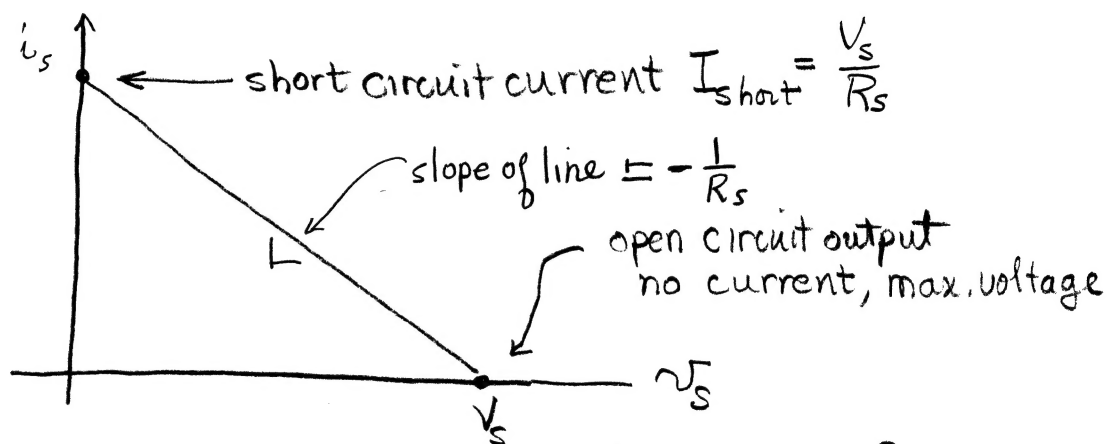1N400x] modest power

What is a load line?   Essentially a power source. It can be a power supply, amplifier, transistor output, etc.

How do we model a power source?   It looks like a Thevenin Equivalent Circuit


What is its i-v characteristic?   a load line

short circuit current $I_{short} = \dfrac{V_s}{R_s}$

slope of line $= -\dfrac{1}{R_s}$

open circuit output no current, max. voltage

Basically a load line is a equation of the possible outputs for a source. The i-v characteristic is a plot of the possible operating points for a device.

Suppose we want to drive a non-linear device like a diode by a source. We can find the operating point by plotting the device's I-v characteristics on the same graph as the source's load line.
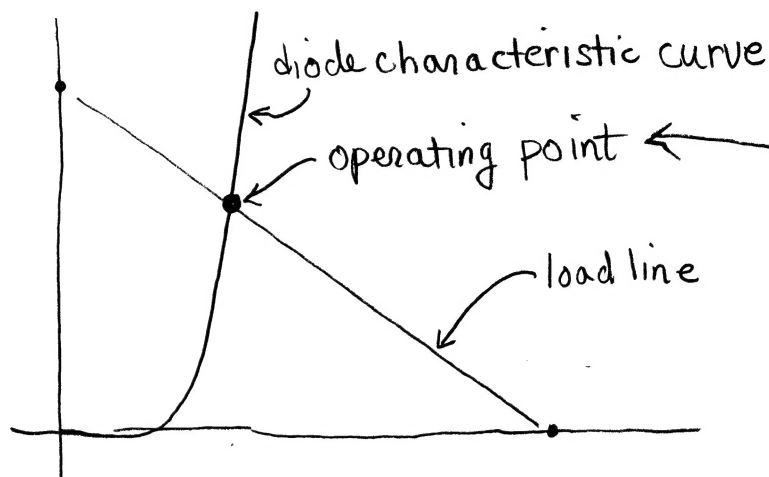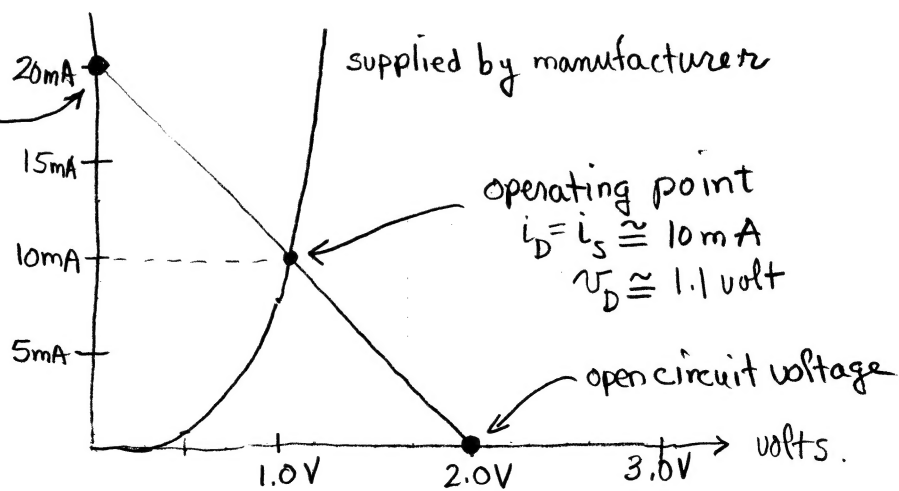

this corresponds to
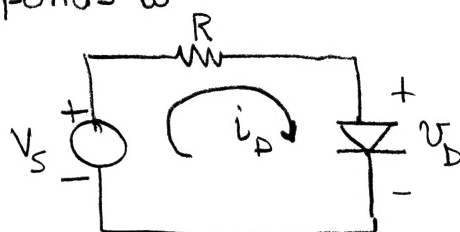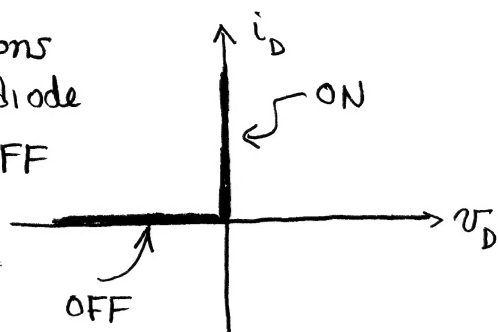

what is i_D?

Since $i_D = i_D$ read from graph

Example: real diode (provided by manufacturer)
power source $V_{SS} = 2V$ $R = 100\,\Omega$

$i_{short} = \dfrac{\varepsilon}{R} = \dfrac{2V}{100}$

$= 20mA$

supplied by manufacturer

operating point
$i_D = i_s \cong 10\,mA$
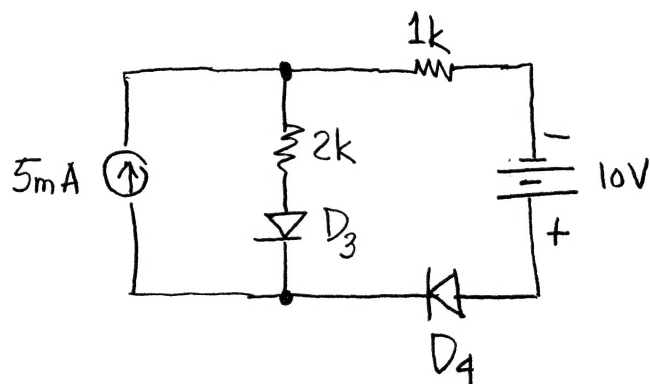$v_D \cong 1.1\ volt$

open circuit voltage

3.3 Ideal diode

for many applications
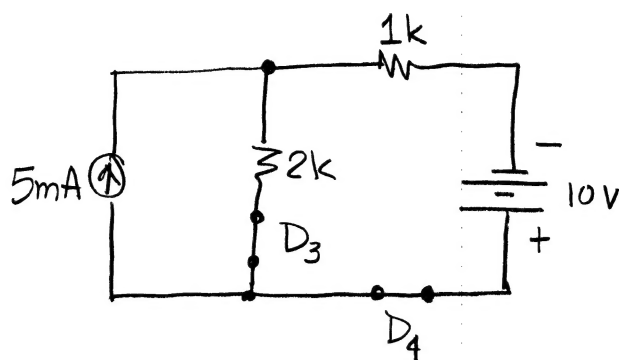we can simplify diode
model to ON/OFF

We can use this model in many circuits problems.

How about a multi-diode circuit like this? Which diodes are ON? which are off?
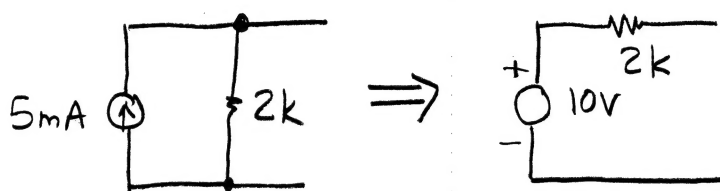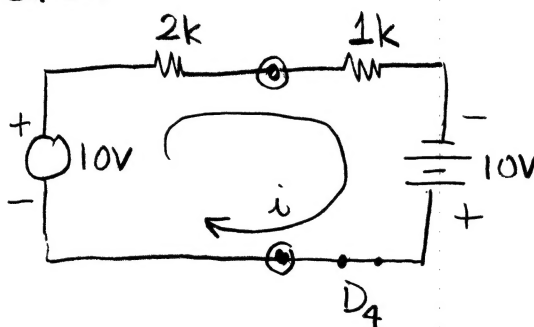
Assume both are ON. Circuit looks like

How would you solve this circuit?
I would use source transformation or superposition

$$U = IR = (5mA)(2k) = 10V.$$

Let's look at circuit

this gives a current
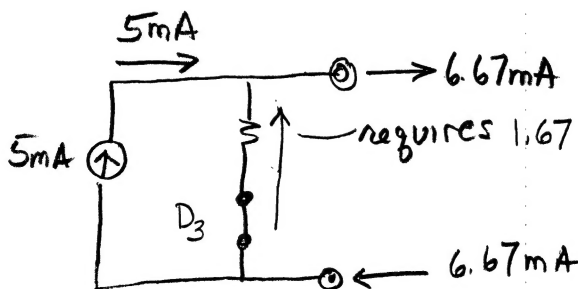
$$i = \frac{10 + 10}{2k + 1k} = \frac{20}{3} mA$$

$$= 6.67 \, mA$$

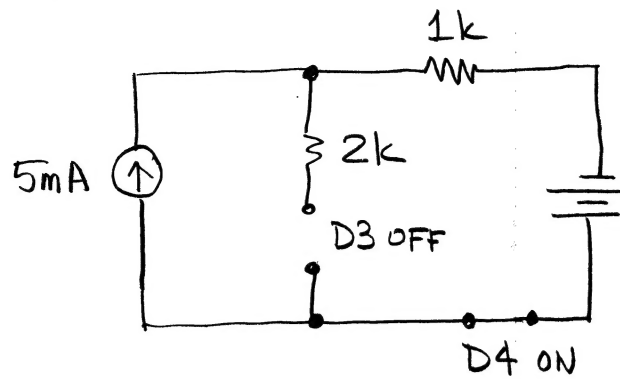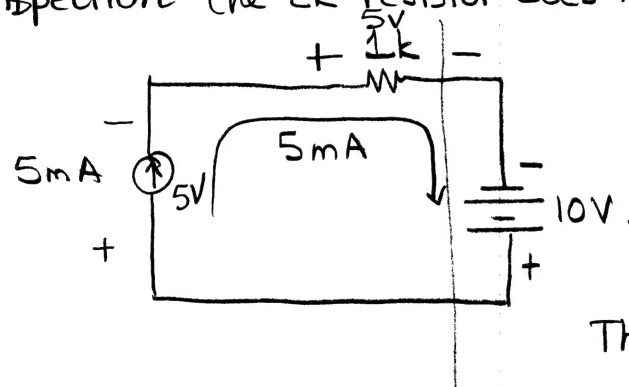∴ D_4 is ON. so this is OK.

How about

requires 1.67 in up direction
This is in violation of assumption.
Current indicates reversed
diode. Assume D_4 ON
and D_3 off and try again.

If D3 OFF, D4 ON circuit looks like this:

by simple inspection the 2k resistor does not contribute anything

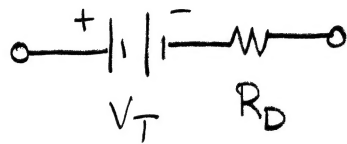Does this circuit work ok?
Let's see.

5mA current thru everything

That puts 5v across 1k resistor.

The resistor's voltage is as shown.

This puts 5V across current source as shown which is ok.

so that $\sum_{loop} v = 0$.

Better diode model:

fit a straight line to "on" region
good fit for reasonable currents.

assume diode is "OFF" below a threshold $V_T \approx 0.6 - 0.7$ volts.
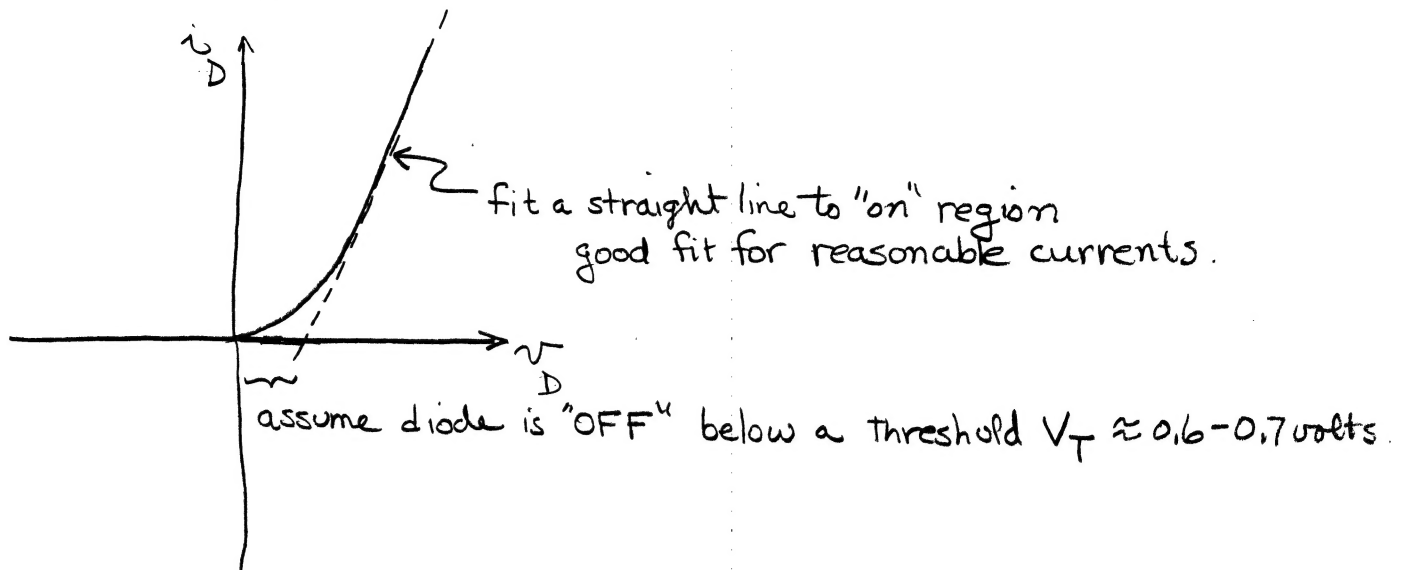
The maximum voltage a diode will withstand is called the

PIV — peak inverse voltage

PRV — peak reverse voltage

3.4 Rectifier circuits

AC source
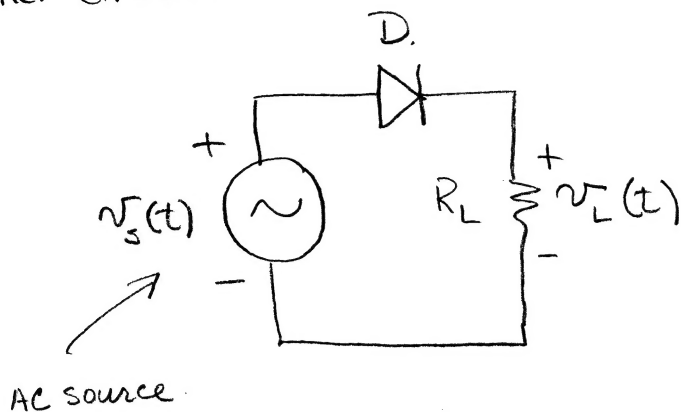
Best analyzed using "ideal" diode model

diode is a "short" when $v_D > 0$
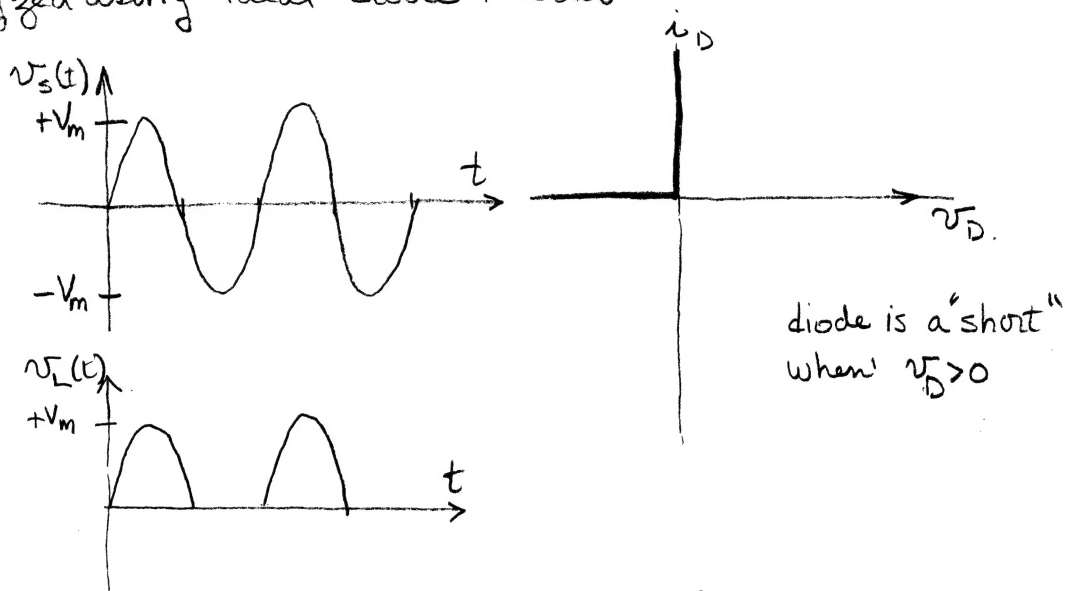
If you would actually measure $v_L(t)$ with a scope in the lab you would see:

lower due to R of diode

It will look a lot like the original sine wave.

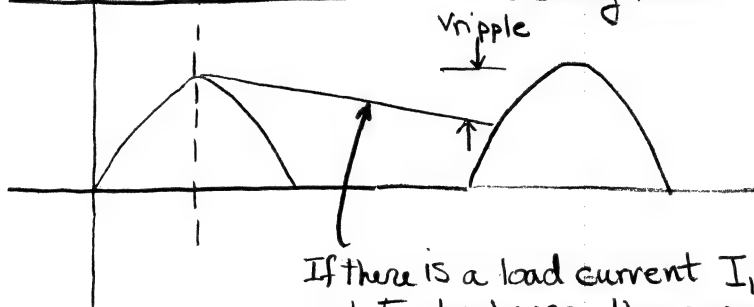not sharp due to gradual nature of "knee"
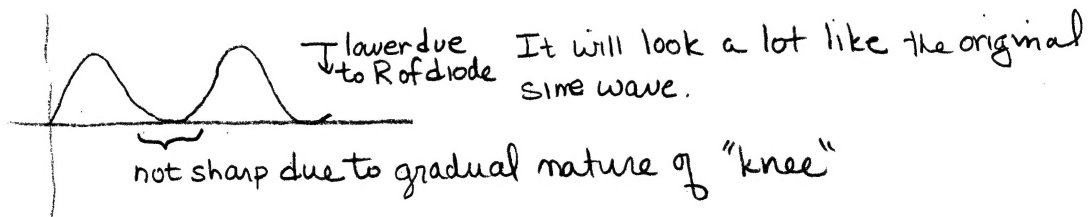
Simple half wave rectifier circuit   (in power supplies, AM radio detectors)

V_m
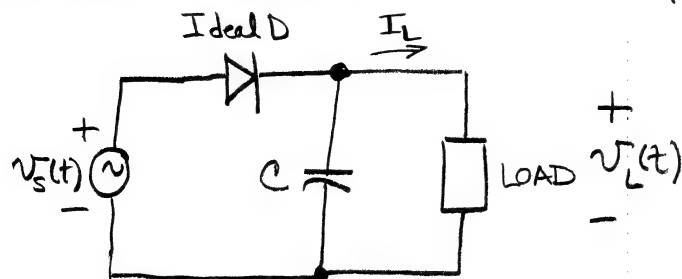
this is what we would see if we had a resistor load.

V_m

If we have just a C as a load the capacitor will change up to V_m and stay there

V_{ripple}

If there is a load current I_L this will act to discharge the capacitor.

Since capacitor is already at $+V_m$ There will be no current flow thru diode.

Let's estimate the voltage drop — called ripple — for a half-wave rectifier with smoothing capacitor.

charge removed from capacitor

$$\Delta Q \cong I_L T$$

approximate by period, $\frac{1}{60 Hz}$.

average load current

definition of capacitance

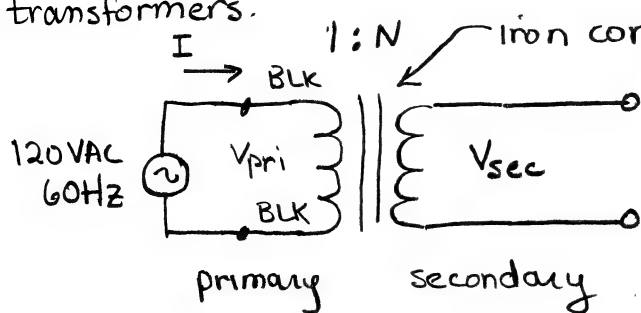$$C = \frac{Q}{V} \qquad or \qquad Q = CV$$

differentiating

$$\Delta Q = C \Delta V$$

$$\therefore \quad I_L T = C \Delta V$$

$$or \quad C = \frac{I_L T}{\Delta V}$$

Power supplies usually actually use full-wave rectifier or bridge rectifier circuits. To study these we need to look at transformers.
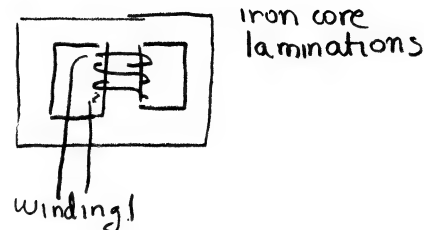

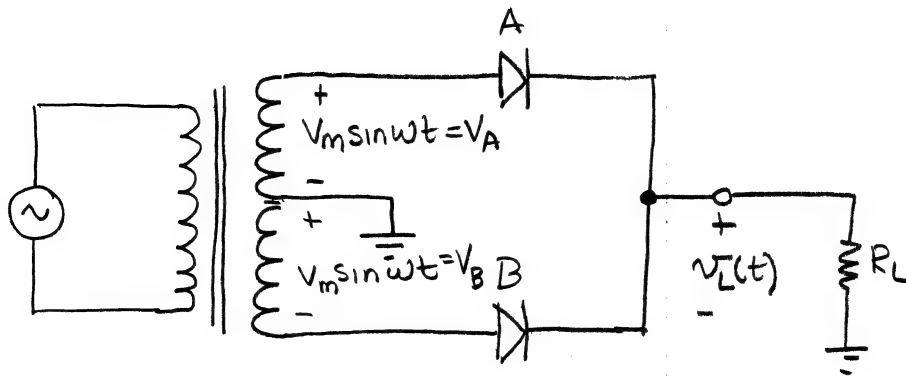$$V_{sec} = N\ V_{pri}$$

$$I_{sec} = \frac{1}{N}\ I_{pri}$$

$$V_{sec}\ I_{sec} = V_{pri}\ I_{pri}$$

transformers are usually very efficient

Transformers are used for:

① changing voltages to more useful voltages efficiently
— most efficient to transmit power at high voltages

② electrical isolation from power lines

— current can actually flow thru people !
— can float output.

③ impedance matching
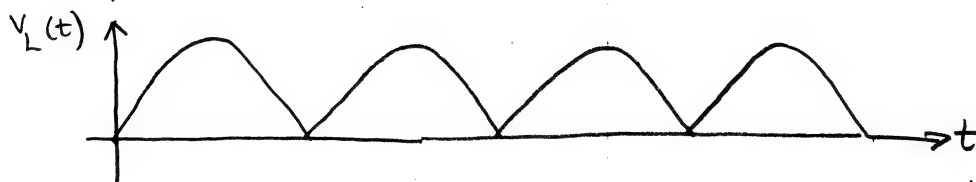
this is called a center-tap

The magnetic fields are in the same direction
so the output looks like two sinusoidal sources
in series.

When $V_A > 0$ diode A conducts, but $V_B < 0$ as seen
by diode B so diode B is OFF

When $V_B > 0$ as seen by diode B it is conducting,
but at that time $V_A < 0$
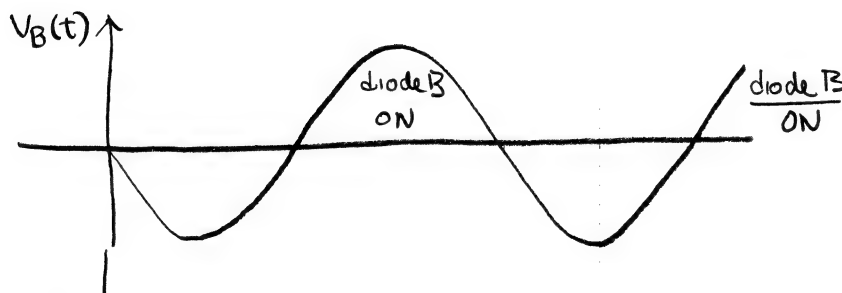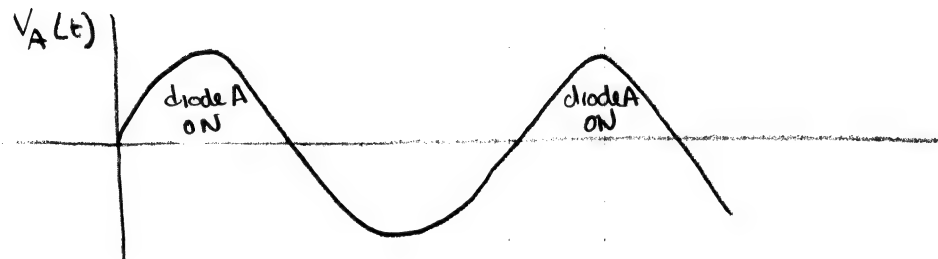
Much less "ripple" than half-wave rectifier

problems

1. requires center tapped transformer

diode bridge

full wave rectifier without center-tapped transformer

commercial diode bridge

positive half-cycle ⊕

negative half-cycle ⊖
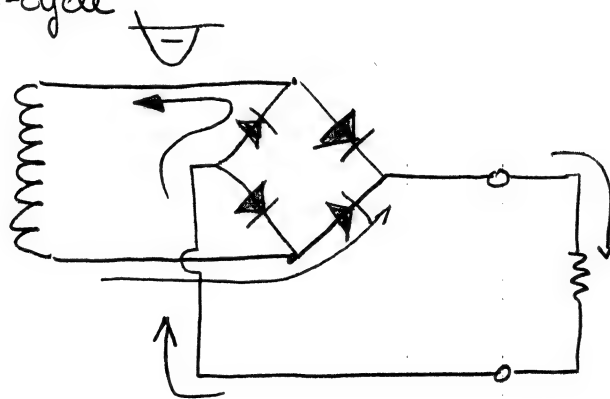
Design choices   p. 712 — 715

①   ripple — full-wave to reduce ripple
      capacitor size

②   maximum load current

     diode peak current

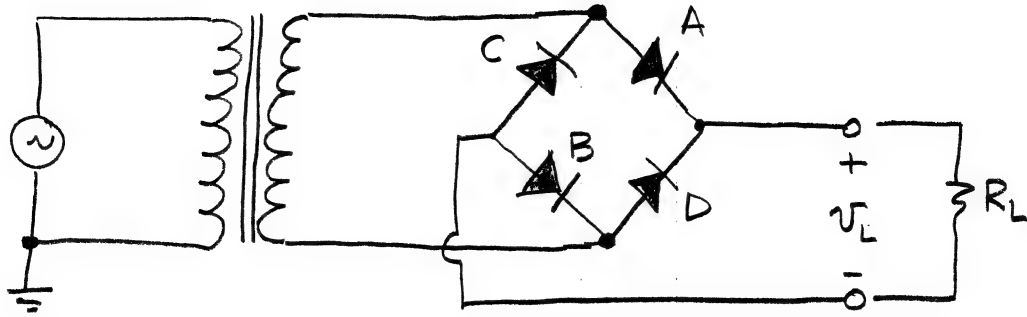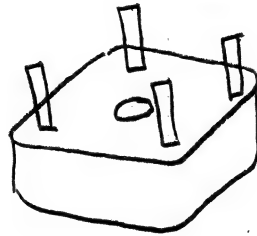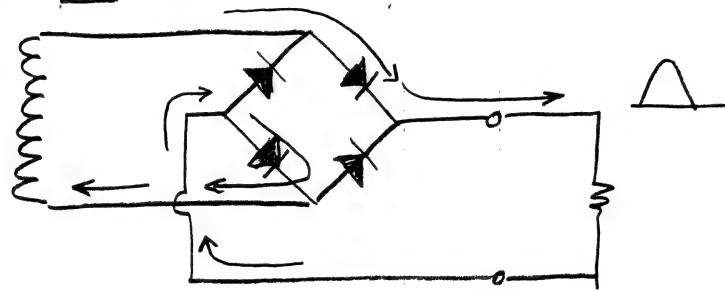   diode surge current

     (diode PRV)

     transformer current

Example 10.8

design 5V DC @ 1A

line voltage   105 — 130 V rms

regulator   ± 10% voltage tolerance, max dropout 2.5V

Minimum allowed input to regulator to prevent dropout

$$\underbrace{5 \times 1.1}_{\substack{\text{upper limit} \\ \text{of regulator}}} + 2.5V = 8V$$

we will design
power supply/filter
to produce this

① use diode bridge
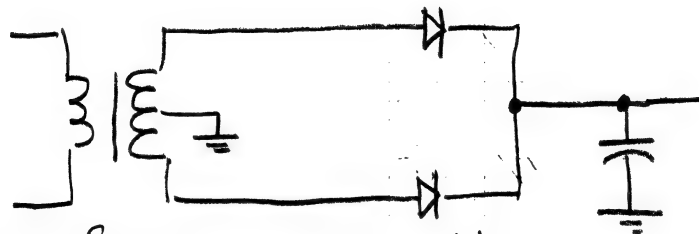
② select transformer current rating

Fig. 10.37(c) $I_{t,rms} \cong 1.2\, I_{L,avg}$

since $I_L = 1A$ $\Rightarrow I_{t,rms} = 1.2A$ pick larger
transformer, maybe 1.5A

③ pick diodes.   Look at 1N400x series.

   identical except for PRV from 50V to 1000V.

   since low voltage supply pick 1N4001

Power supply is 1A out average
   ⇒ each diode should be $\frac{1}{2}$ A average forward current

However, peak currents several times larger.

   measurements from test circuit give
      peak diode currents 5-20A

data sheet says $V_{diode} \cong 1.5$ Volts for these currents.

④   Pick transformer voltage.

   transformer resistance causes voltage drop
      ⇒ allow 10% drop   near load current rating

$$V_{oc,peak} = V_{L,min} + V_{diode} + V_r + V_{drop}$$

$\underbrace{\phantom{V_{oc,peak}}}$	$\underbrace{\phantom{V_{L,min}}}$	$\underbrace{\phantom{V_{diode}}}$	$\underbrace{}$	$\underbrace{\phantom{V_{drop}}}$
transformer secondary	use 9 rather than 8 for device tolerance	1.5V @ peak currents	ripple $V_{r,p-p}$ =2V	transformer resistance ≈1v

$$V_{oc,peak} = 9 + 1.5 + 2 + 1 = 13.5 \text{ Volts peak}.$$

Worse case :   105 input (lowest) producing 13.5 V peak (max).

At 120 Volts this transformer would produce

$$V_{oc,peak} = 13.5 \times \frac{120}{105} = 15.4 \text{ Volts}.$$

$$V_{oc,rms} = 15.4 (0.707) \cong 10.9 \text{ Volts}.$$

For ±10% regulation we pick minimum as $10.9 - 1.09 \cong 9.9 v$.

   ⇒ we need at   9.9 V_{rms} transformer.
      (19.8V CT)

⑤ Now select capacitor

P-P ripple is 2 volts.

$$C = \frac{I_L T}{2V_r} = \frac{(1A)(\frac{1}{60})}{2(2)} = 4167\,\mu f$$

What is voltage rating

If we use an 10 volt ct transformer, 1.5A sec, with 10% regulation

From Example 10.7   Transformer model

regulation of transformer

$$\frac{V_{oc} - V_{fl}}{V_{fl}} \times 100\% = 10\%$$

$V_{fl} = 10$ volts rms (i.e. full load voltage)

Then $V_{oc} \cong 11\,V\,rms$ (15.6 volts peak).

Use peak value under worse case.

$$15.6\left(\frac{130}{120}\right) = 16.9 \text{ volts,}$$
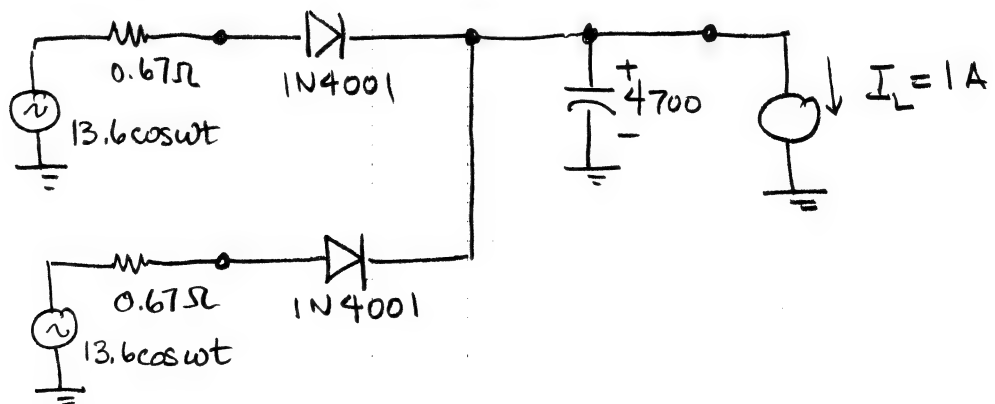
∴ use 20V capacitors

Computer model

$R_t = \dfrac{V_{oc} - V_{fl}}{I} =$

$R_t = \dfrac{11 - 10}{1.5}$

$\underline{R_t = 0.67\,\Omega}$

use xfmr worse case
i.e. 105 V.
Then peak reduces to
$$15.6\left(\frac{105}{120}\right) = 13.6$$

Thevenin

Reading T&R 3.4 (pgs. 105 – 109) Thevenin, Norton

          (pgs. 115 – 118)   non-linear loads

      4.2 (pgs. 163 – 164) circuits w/ dependent sources.

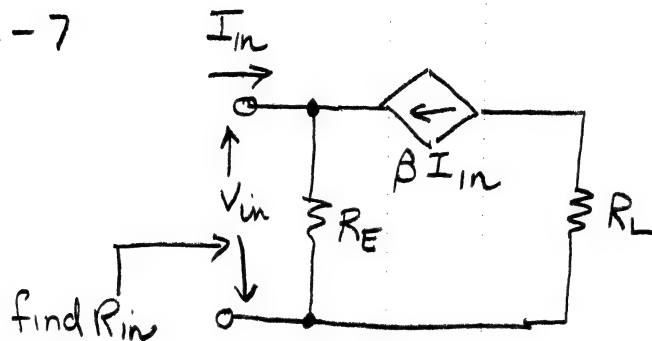 Possible problems.

     4.4, 4.5

  Hambley problems: 3.17 (Ideal diode model)

          3.20, 3.24 (Rectifier Circuits)

          3.22, 3.35 (Wave-shaping circuits)

          D3.38 (Design a clamp)
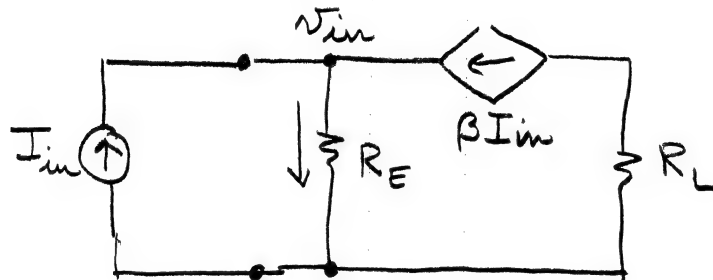
Thevenin Equivalent Circuits

For circuits with active (controlled) circuits
leave independent sources ON or use external test circuit.

$\Rightarrow$ find open circuit voltage
short circuit current

Example 4-7

find R_{in}

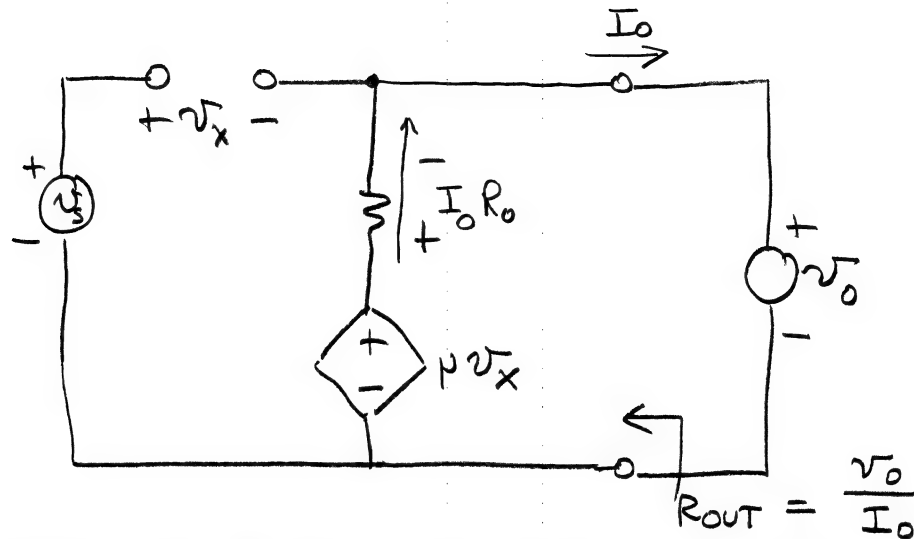Use a test source, calculate v_{IN}. Then $R_{in} = \dfrac{v_{IN}}{I_{in}}$

use KCL at input.

$$\sum_{+in} i = 0$$

$$+ I_{in} + \beta I_{in} - \frac{v_{in}}{R_E} = 0$$

$$(\beta + 1) I_{in} = \frac{v_{in}}{R_E}$$

$$R_{in} \equiv \frac{v_{in}}{I_{in}} = (\beta + 1) R_E$$

Example 4-8

$$R_{OUT} = \frac{V_o}{I_o}$$

can't use a test current source — try it!

do KVL on inner loop

$$-\mu V_x + I_o R_o + V_o = 0$$

⎣ get rid of this variable
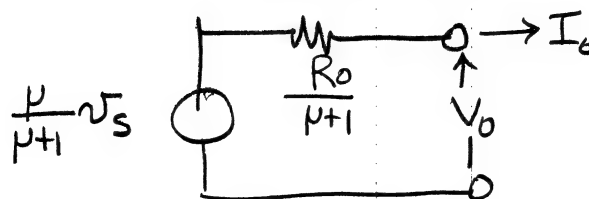 by doing outer loop.

$$- V_s + V_x + V_o = 0$$

Eliminate V_x

$$-\mu(V_s - V_o) + I_o R_o + V_o = 0$$

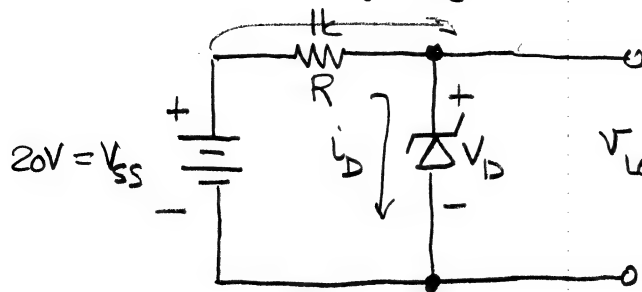$$-\mu V_s + \mu V_o + I_o R_o + V_o = 0$$

$$-\mu V_s + (\mu+1) V_o + I_o R_o = 0$$

Since voltage source try writing V_o

$$V_o = \underbrace{\frac{\mu}{\mu+1} V_s}_{\substack{\text{looks like a} \\ \text{voltage source}}} - I_o \underbrace{\frac{R_o}{\mu+1}}_{\text{looks like a resistance.}}$$

Sect. 3.7   Zener diode voltage regulator

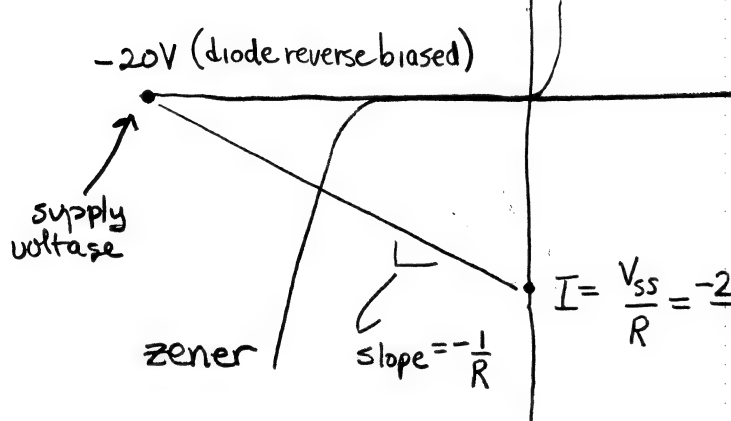$V_{LOAD} = -v_D$ $\left(\begin{array}{c}\text{negative since}\\\text{in 4th quadrant}\end{array}\right)$

use load line analysis to find operating current.

using KVL
$$-V_{SS} + i_D R_D + v_D = 0$$
                  ↑   ↑
          these are both negative

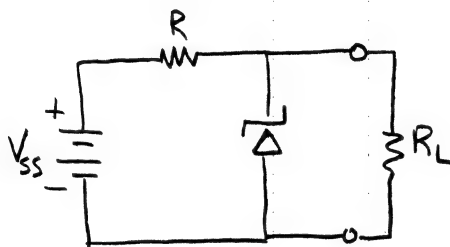

zener operates in 3rd quadrant

$I = \dfrac{V_{SS}}{R} = \dfrac{-20V}{1k} = -20 mA$.

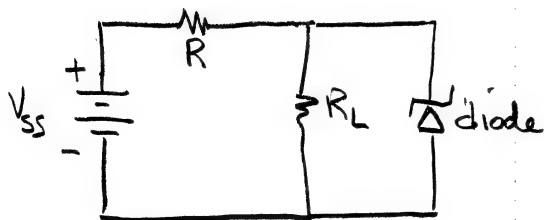If you know V_Z the zener voltage, the supply voltage, and R you can always calculate I.

However if we must design a zener diode voltage regulator for a known load.
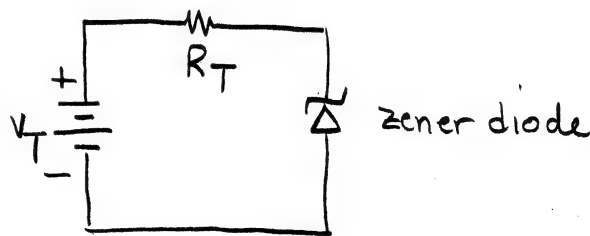
Practical circuit

This represents the load. If $R_L \rightarrow \infty$ all current goes through the zener.

Solution method

collect resistors & thevenize

The design works best for relatively constant loads. If R_L should change this poses problems.
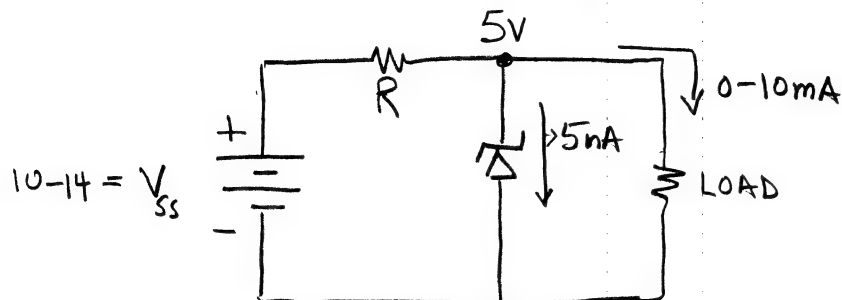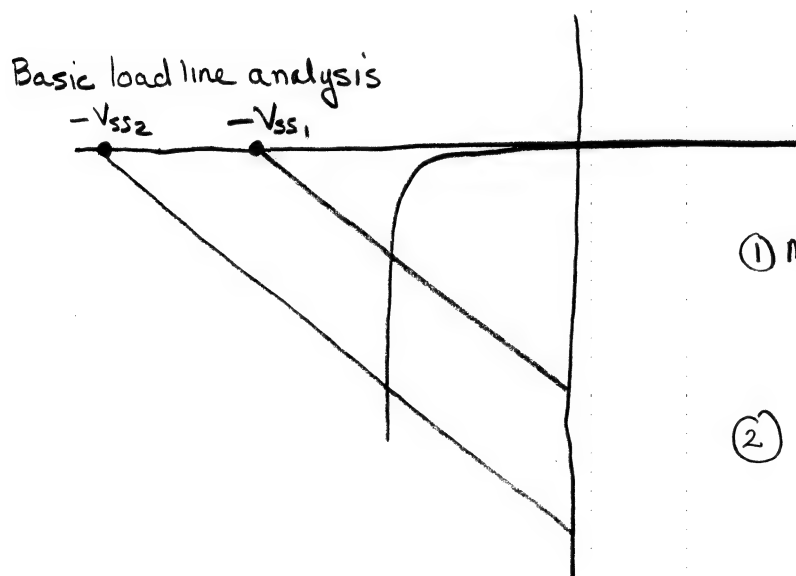
Prob
3.46 Design 5V zener diode regulator
       operates from a source that varies 10-14V
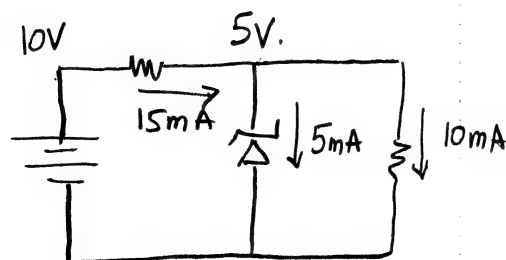   load current varies from 0-10mA
       Determine R so that $|I_d| \geqslant 5mA$

           5V

     R

   $10-14 = V_{ss}$ $\gg 5nA$ LOAD

       0-10mA

       Consider that $V_D = $ constant $+5$ volts.
              R is fixed

Basic load line analysis
   $-V_{ss2}$ $-V_{ss1}$

① minimum current for lowest
   V_{ss}. This should have been
   intuitive.

② Minimum I_d occurs when
   $I_L = $ maximum. Since V_D
   is constant the total current
   is constant.
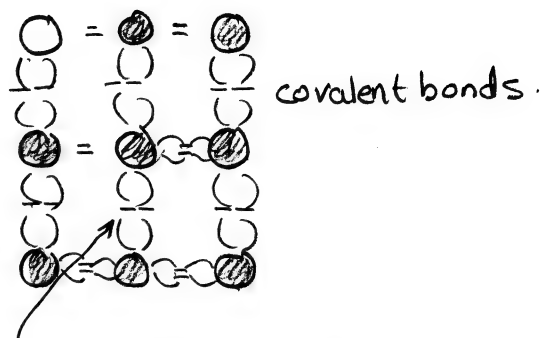   If $I_L = 0$ then $I_d = 15mA$
   If $I_L = 10mA$ then $I_d = 5mA$.

design   10V   5V.

        15mA   5mA   10mA

③ $R = \dfrac{V}{I} = \dfrac{10V - 5V}{15mA} = \dfrac{1}{3}k = 330\Omega$

3.9 Basic Semiconductor Concepts

- most semiconductor devices are silicon although others are possible

intrinsic silicon crystal
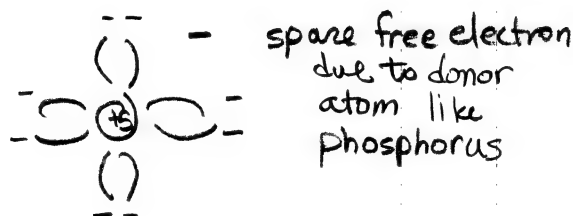   4 atoms in outermost
        valence band

covalent bonds.

Thermal energy can break bond
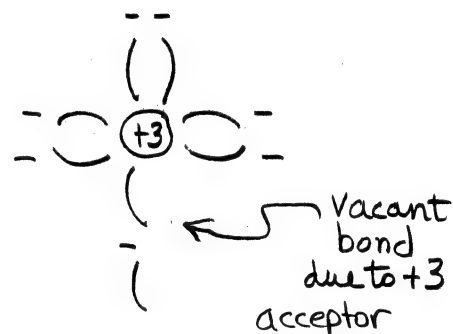   fixed vacancy
    free electron

free electrons & holes generated by thermal energy → better conduction at
(when a free electron encounters a hole   recombination) high T's
                                              occurs.

n-type semiconductor

— spare free electron
    due to donor
    atom like
    phosphorus

p-type semiconductor

Vacant
bond
due to +3
acceptor

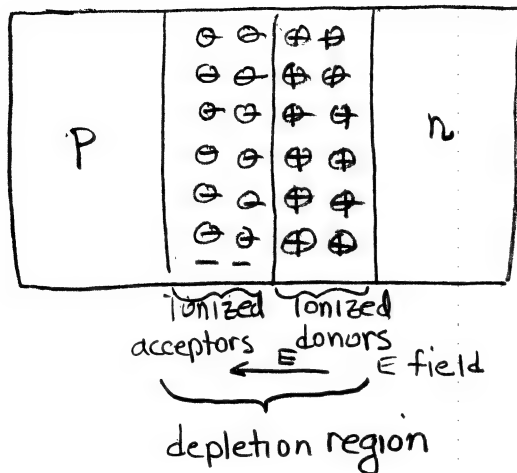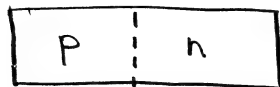Charge = 0 $n = p + N_D$

free   holes   donor
electrons   concentration

                       this is what
                       tips the balance

$p = N_A + n$

holes   ionized   free
         acceptor   electrons.
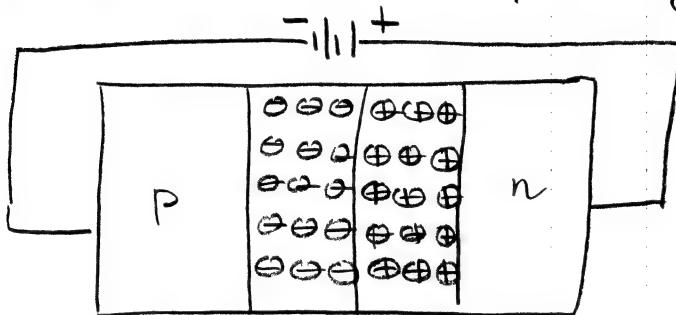   atoms

3.10   unbiased p-n junction

When we put the p & n materials together diffusion occurs

excess holes $p \rightarrow n$

free electrons $p \leftarrow n$
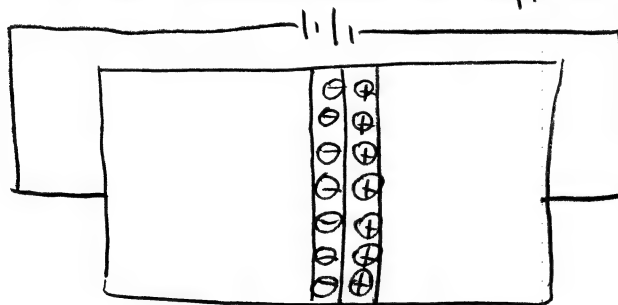
The result is that the bound charges remain.

If we reverse bias the depletion region increases.

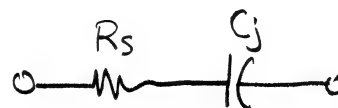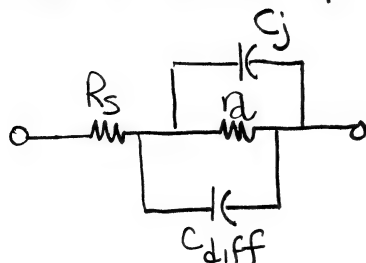
reverse bias pulls out the carries.

Increases the electric field making it harder for current to flow.

If we forward bias the depletion region decreases.

Gives rise to more complete diode model.
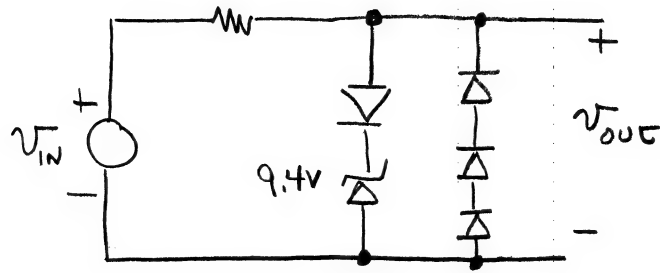

C_{diff} = forward bias

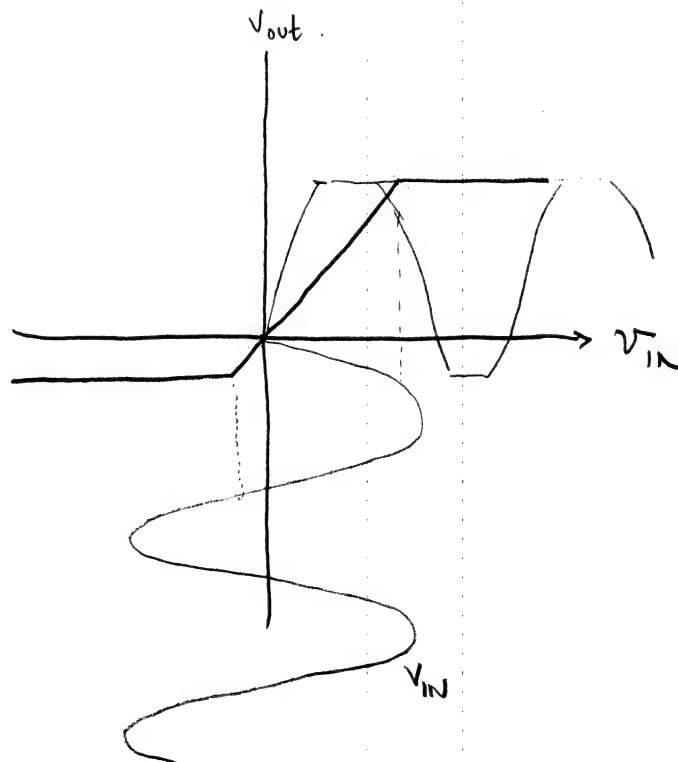C_j = depletion capacitance

R_s = bulk ohmic resistance
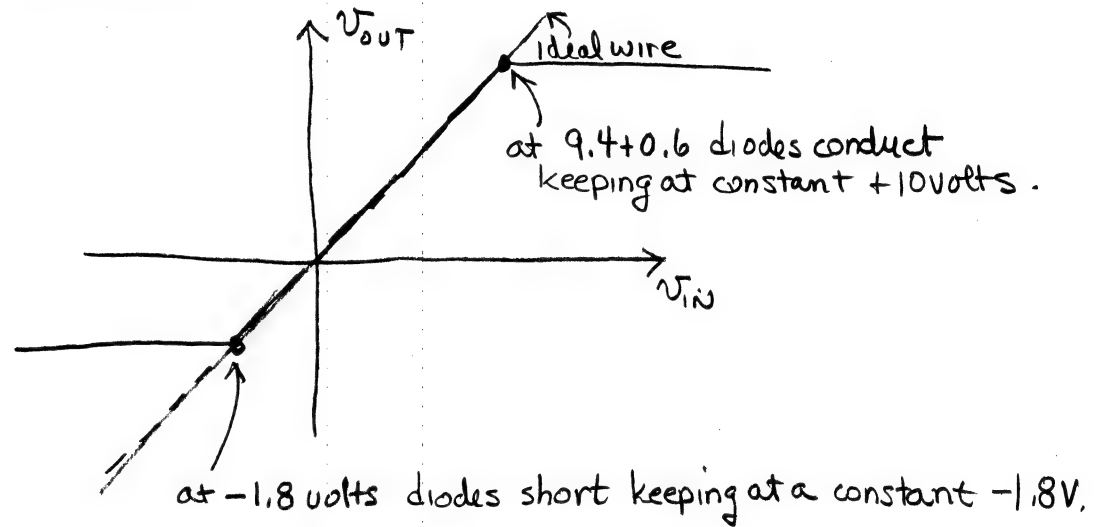
r_d = dynamic resistance

Clippers, Clamps, Diode Logic

2.17(a)

Assume ideal diodes with 0.6 Volt offsets.

ideal wire

at 9.4+0.6 diodes conduct keeping at constant +10 volts.

at −1.8 volts diodes short keeping at a constant −1.8V.
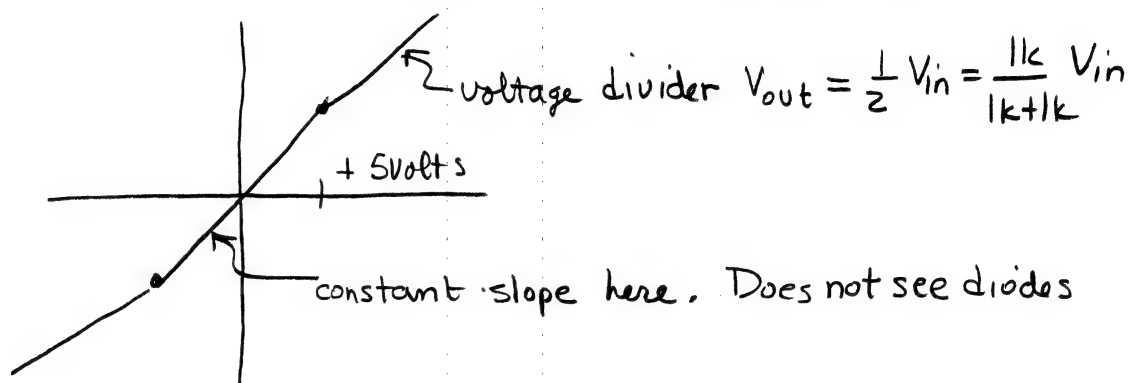
diodes can also change slope.

3.7(b)

1k

4.4V

4.4V

1k
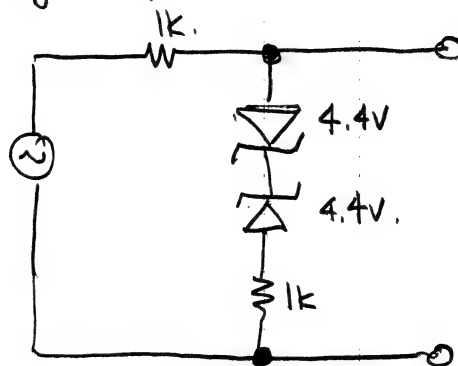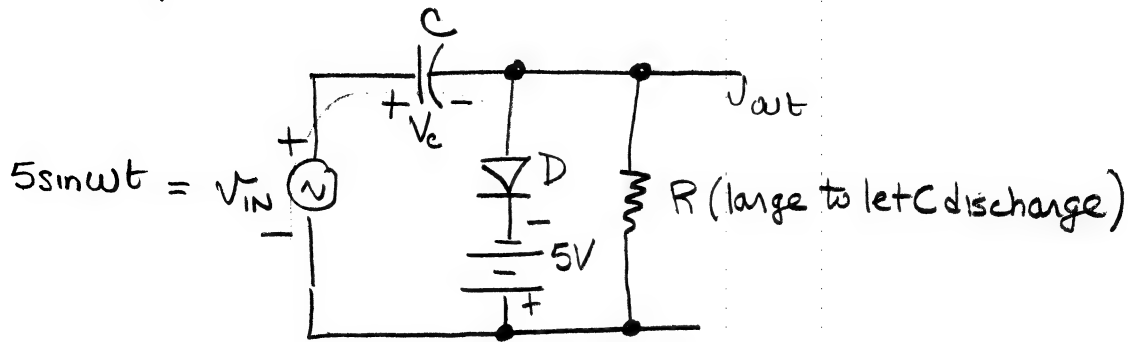
what do the zeners do : conduct in forward direction with 0.6 V drop
and in reverse direction at 4.4 volts.

voltage divider $V_{out} = \frac{1}{2} V_{in} = \frac{1k}{1k+1k} V_{in}$

+ 5 volts

constant slope here. Does not see diodes

Clamps are circuits which insert DC components.

$5\sin\omega t = V_{IN}$

C

V_c

D

5V

R (large to let C discharge)

V_{out}

The capacitor is initially charged by the battery to +5 through D
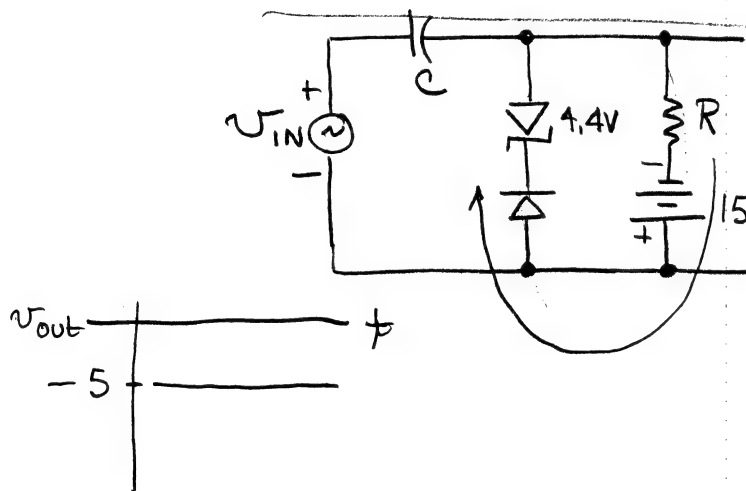
If V_{IN} increases above 5 volts, the diode conducts
and V_c will charge to the peak input value. It (c) charges
to the (peak value of the input + 5) volts

V_{out}

-5

-10

-15

t
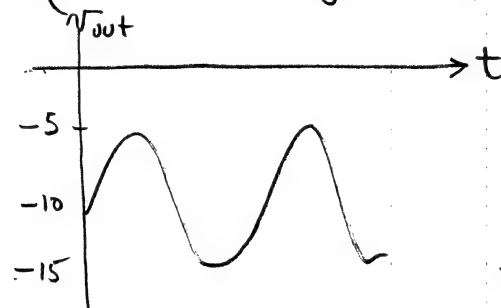
Capacitor always
charges to V_{peak} of input

i.e. $V_c = V_p + V_R$

If $V_{peak} = 5$ volts then
we get this output.

V_{IN}

C

4.4V

R

15

V_{out}

-5

similar to above circuit but battery
causes current flow through
diodes. Diodes have a voltage
drop which is $0.6 + 4.4 = 5$ volts
and is in parallel with C
Thus, C charges up to +5 volts
as above from battery.

However, V_{IN} does not forward bias diode
That is done by the 15 volt battery. Thus,
the battery keeps the diode branch at about 5 volts
through a parallel branch.

The difference between the two circuits is whether the battery is
in series with V_{IN}.

Some exotic diode applications for a clamp

DC restoration in television circuits

video signal

retrace

black (dark)

white (bright)
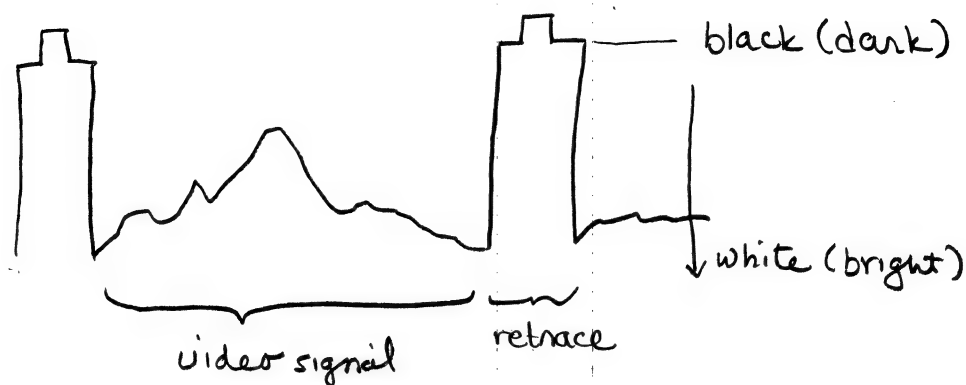
Running a video signal through an ac amplifier will shift its DC level. Yet television uses DC level to establish brightness. Use a clamp to restore proper DC levels.

Use diode clamp to restore to
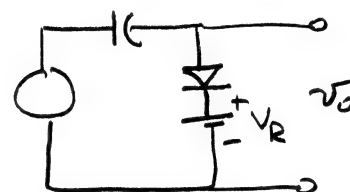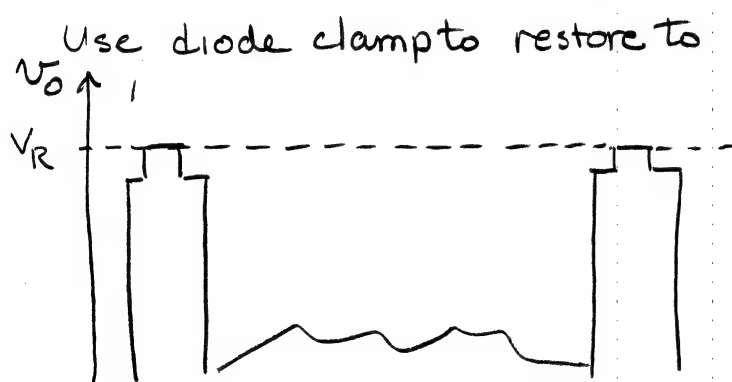
Voltage doubler

diode clamp   peak rectifier
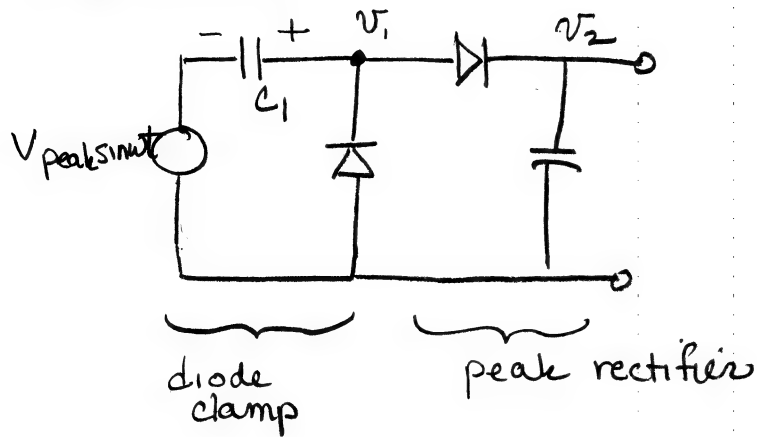
diode clamp charges to $+ V_{peak}$ as shown.
This shifts ac waveform up as shown.
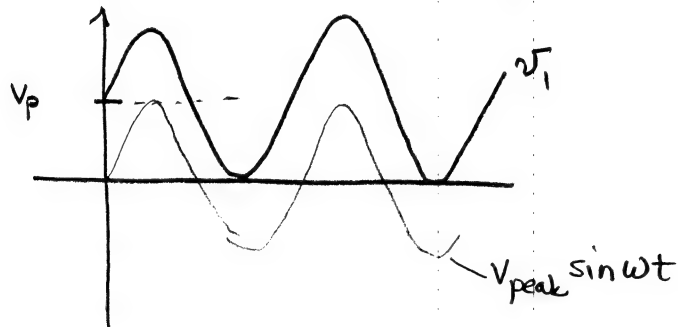
The peak rectifier operates just as discussed earlier.

$$\Delta V = \frac{I_L T}{C}$$

load current

diode logic circuits

if V_A OR V_B OR V_C = +5 volts then V_{out} = 5 volts. else V_{out} = 0.
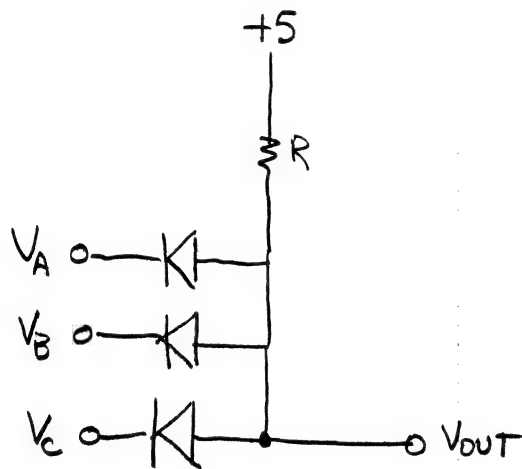
if V_A AND V_B AND V_C = +5 volts then V_{OUT} = +5 volts else V_{OUT} = 0

diode analog switches
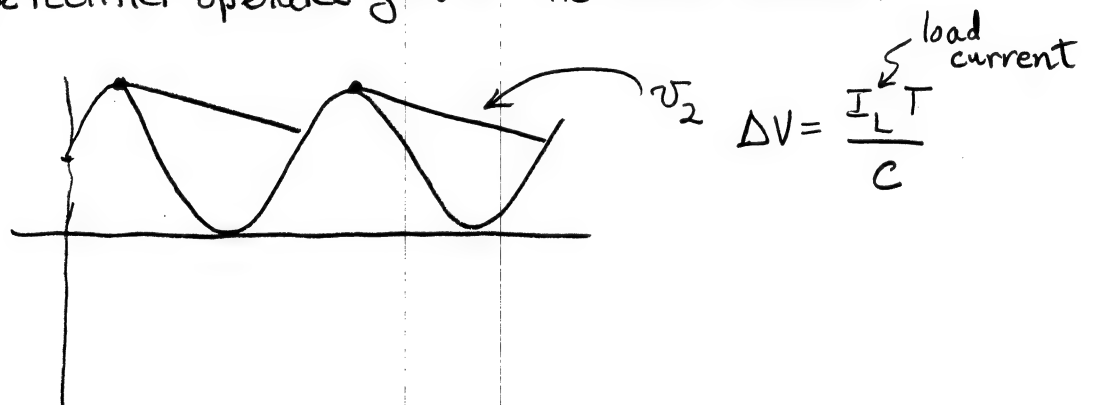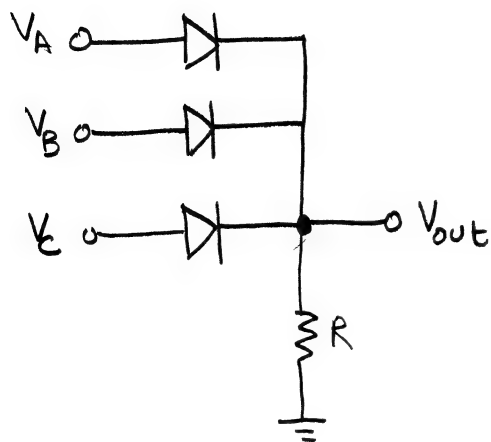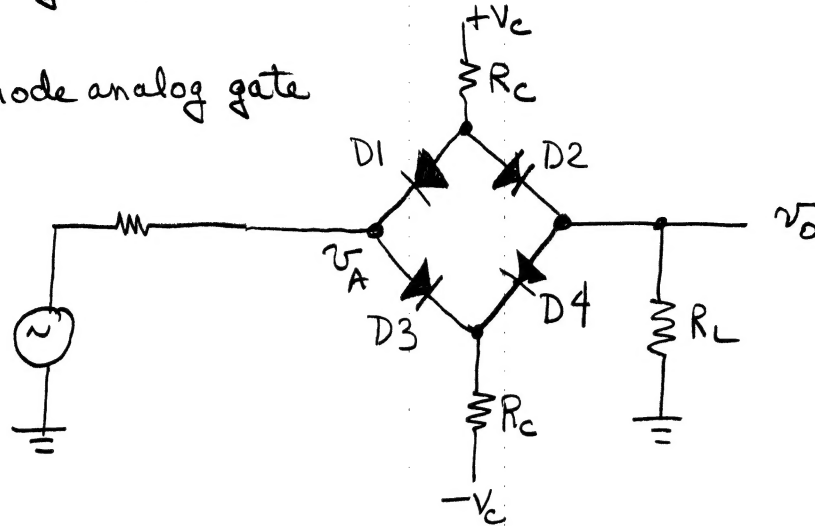
usually done with transistors but diodes are faster

four-diode analog gate

$+V_c$

R_c

D1 D2

v_A

v_o

D3 D4

R_L

R_c

$-V_c$

If $V_c > 0$ then then all diodes forward biased.
and $v_o = v_A$

If $v_c < 0$ then diodes OFF (reversed biased and no
output.

There are some restrictions such that the diodes remain
forward biased.

$+V_c$

i_s R_c

i_c

1.

i_c

$+$ $-V_T$ $+$ V_T $-$

R_1

$+V_T$ V_T $+$

v_{IN}

v_o

i_s

R_L

i_s

R_c

$-V_c$
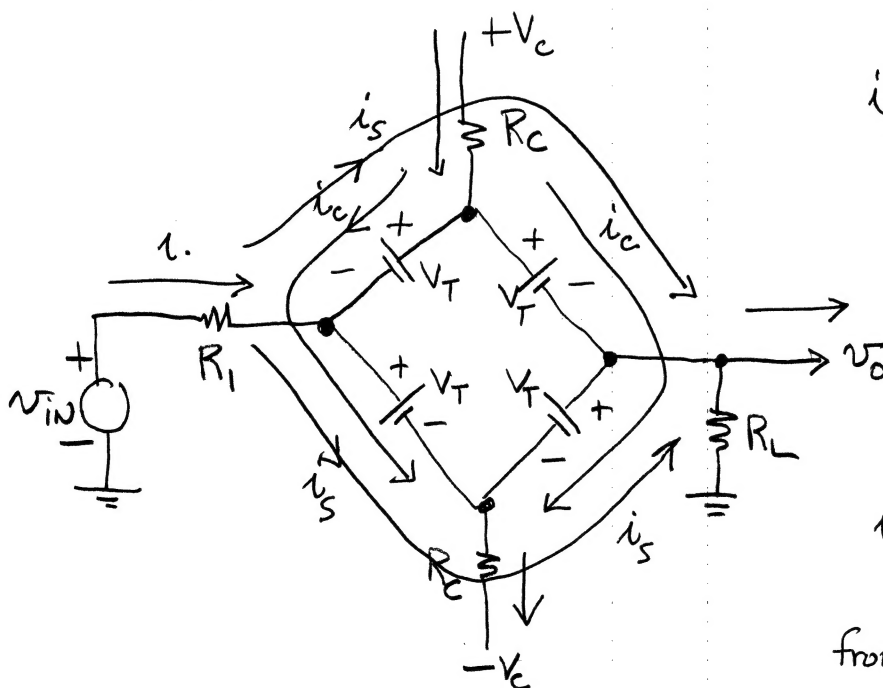
$$i_c = \frac{2V_c - 2V_T}{2R_c}\left(\frac{1}{2}\right)$$

each current is $\frac{1}{2}$
since it splits

$$i_s = \frac{v_{IN}}{R_1 + R_L \| \frac{R_c}{2}}\left(\frac{1}{2}\right)$$

from R_1 load looks like
$R_L \| \frac{1}{2}R_c$

Condition is that $i_s < i_c$ in D1 and D4.
for

Chapter 1

1.6 Power Supplies and Efficiency

$$P_i + P_s = P_o + P_d$$

← power dissipated

← output power

← power from power supply

← input power (usually small).

Efficiency of a power <u>amplifier</u> η is the percentage of the power supply that is converted into output power.

$$\eta = \frac{P_o}{P_s} \times 100\%$$

Example 1.4.

Power input to amplifier = 10^{-11} watts.

Output voltage is 8V rms into 8 ohms.

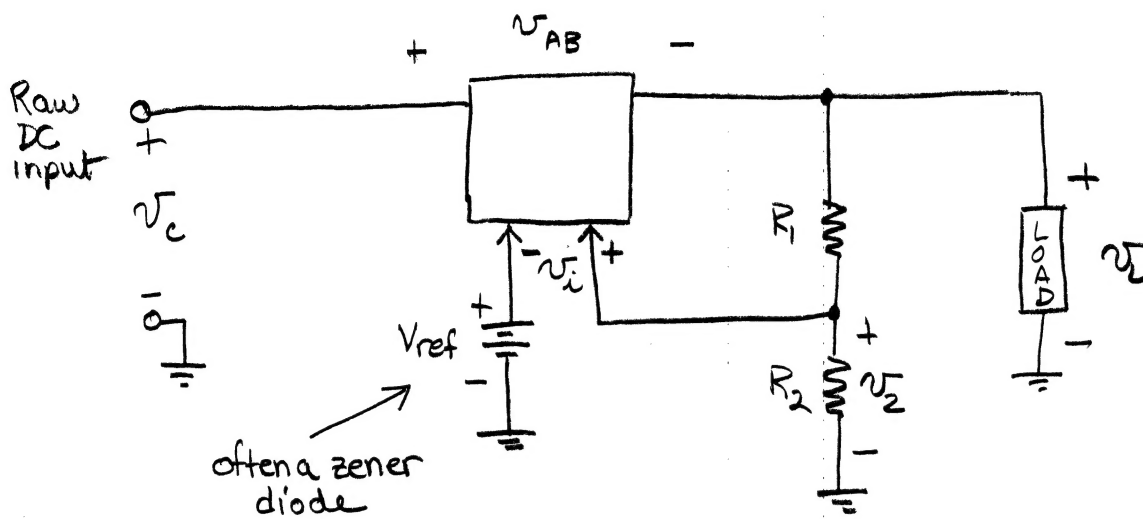$$P_o = \frac{V_o^2}{R_L} = \frac{(8)^2}{8} = 8 \text{ watts.}$$

Power supply is supplying +15V @ 1A, −15V @ ½ A

$$P_s = (15)(1) + (15)\left(\tfrac{1}{2}\right) = 22.5 \text{ Watts.}$$

$$\eta = \frac{8}{22.5} = 35.6\% \qquad \text{typical stereo amplifier}$$

10.5 Linear Voltage Regulator

Series voltage regulator

$$v_2 = \frac{R_2}{R_2 + R_1} \, v_L = \beta \, v_L \qquad \beta \equiv \frac{R_2}{R_1 + R_2} \quad \text{voltage divider ratio}$$

$$v_i = \beta v_L - V_{ref.}$$

Model the regulator as an amplifier (voltage)

$$v_{AB} = A v_i$$

$$v_{AB} = A(\beta v_L - V_{ref})$$

From input to output

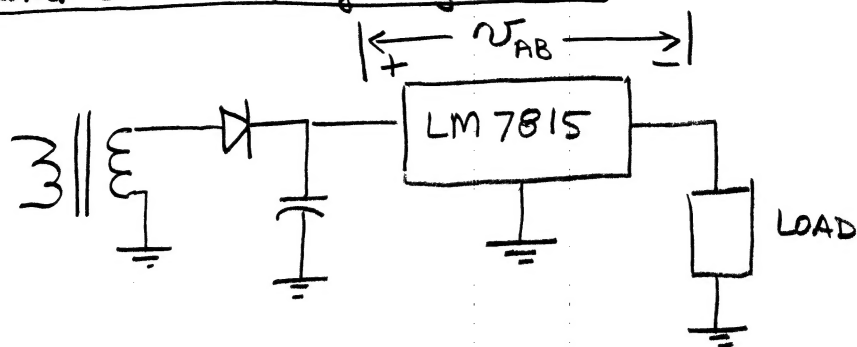$$v_c = v_{AB} + v_L$$

$$v_c = A(\beta v_L - V_{ref}) + v_L$$

Solve for v_L

$$v_c = A\beta \, v_L - A V_{ref} + v_L$$

$$v_L = \frac{v_c}{A\beta + 1} + \frac{A \, V_{ref}}{A\beta + 1}$$

If $A\beta \gg 1$ $\qquad v_L \cong \frac{V_{ref}}{\beta}$

Integrated Circuit Voltage Regulators

Good for nominal output voltages of 2.6V to 15V.

minimum V_{AB} is known as the dropout voltage

Linear voltage regulators require $V_{AB} \geq$ minimum

This comes from regulator specs. Typically 2 to 2.5V for 78xx.

Diode Currents

When the capacitor is initially being charged there is a surge current.

As a result we must select diode for surge current.
  1N4002 is rated for 30A surge for one cycle.

Steady state diode current is given by sum of
  (1) load current
  (2) regulator
      (a) feedback network
      (b) voltage reference
      (c) power to electronics (amplifier)

Peak current is usually several times steady state value.
        (5-20)

Transformer current rating should be several times average.
  Remember winding resistance in modeling.